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Model Based Systems Engineering in Modular Design – A Potential Analysis using Portal Type Scraper Reclaimers as an Example

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Abstract

Many industries have to react progressively to the increasing customer requirements regarding the individualization of products. As a consequence, companies are using more and more standardization methods, such as modular, platform or type series design. This leads to an increased complexity of product development processes and thus to the necessity of concepts which allow a consistent representation of constructions kits. Model Based Systems Engineering (MBSE) can support the development of such systems. A case study carried out in cooperation with thyssenkrupp Industrial Solutions shows the potential of the approach using the industrial sector, the machinery and plant engineering industry as an example.

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Keywords: MBSE; Modular Design; Product Generation Engineering

1. Introduction

The competitiveness of a company is directly associated with the acceptance of the offered product portfolio by the customers. The increasing individualization of customer requirements and the dynamic changes in the modern society and hence on the sales markets lead to a growing importance of a differentiation of a product portfolio in future. [1, 2]

In many companies, the diversity of variants has grown continuously, at product level as well as at assembly and components level, over the past decades. The reasons for this are diverse: The customer requirements, for example, are nowadays more and more differentiated so that products are adapted to the individual customer requests. In addition to that, there are the increased dynamic in innovation and technology, a massive shortening of development times and product lifecycles as well as the effects of the information and knowledge society. [3]

Especially, companies in the field of the machinery and plant engineering industry are operating in the environment of these developments. Due to the growing competitive pressure in the global market environment, the producing companies in this sector have to accept the increasing customer requirements regarding the individualization of plant machinery technology. The management of the continuously growing diversity associated with the increase in complexity of a product portfolio is a real challenge.

The dangers of an exploding diversity of variants include but are not limited to non-transparent development and manufacturing costs as well as an increased development and innovation risk. Furthermore, products and processes become more susceptible to external and internal influences, such as fluctuations in demand or technical modifications. Thus, variant management should be considered as a very important activity in product development. [3]

2. State of the Art

First, the development of products in modular design will be discussed and the necessity of a consistent representation of construction kits and products will be shown. The Model Based Systems Engineering (MBSE) is one possible approach to encounter the challenges in modular design. After a short introduction into MBSE in general, preliminary work in the context of construction kit development will be presented.

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2.1. Modular Design

There are extensive publications on the development of modular products, also the term modularization is often used in this context. These studies deal with the analysis of existing – not yet modular – product generation in order to define suitable interfaces and module characteristics. For instance, the required number of module characteristics has to be defined to enable the desired external product variance for customers [4, 5, 6, 7]. The modular products of a construction kit are often not developed at the same time, but rather in a temporal offset. Thus beside the modularization the construction kit development should be researched closer. It is understood as a concurrent activity in order to develop modules and products within product development [8]. In figure 1 this is shown [9].

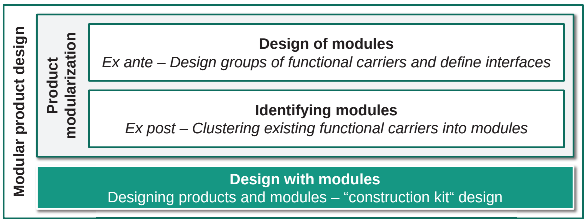

Figure 1: Construction kit development process [9]

Especially for complex products, the aims, features and the design of a product as well as their interactions are not transparent. Therefore various studies demonstrate the necessity of an iterative approach [10, 11] to fulfil the uniqueness of product development processes [12]. Thus, the development of construction kits and their corresponding modular products must be considered as a continuous activity which starts with the development of the first product and ends with the completion of the last development project [8]. Within this ongoing activity, there are strong interactions between all systems [13]. As an example, figure 2 shows products which are based on a construction kit and use same modules [8].

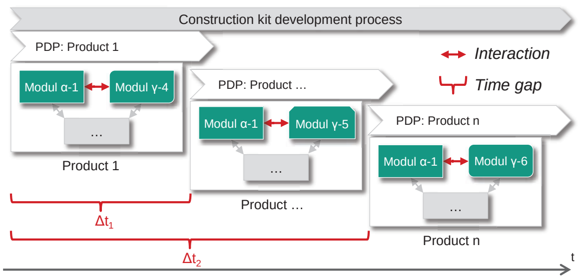

Figure 2: Construction kit development process [8]

This creates different challenges. On the one hand, the uncertainty increases by the great temporal offset and on the other hand, dependencies are created which have to be considered. The uncertainty arises due to the fact that elements of a construction kit must be developed today for products whose development starts not until some years later. On the basis of the temporal offset, some systems will be developed only some time later to fulfil new objectives such as, for example new customer or legal requirements [8].

The compatibility between the modules of complex products cannot be guaranteed by a standardization of the interfaces alone [13]. This is due to the fact that individual effects are a result of the interaction of several subsystems. This is called emergence. [14]. The dependencies between the modules additionally causes that necessary adjustments to a module must be coordinated with the developers of the different products. For this, product developers need a common basis for communication which enables a consistent representation of the construction kit and of the associated modular products. Model Based Systems Engineering (MBSE) can support the development of such systems. Thus this approach is presented below.

2.2. Model Based Systems Engineering

Systems engineering is an interdisciplinary approach that concentrates on the definition and documentation of systems requirements, the preparation of a system design and the verification of the system to compliance with the requirements [15, 16]. Model Based Systems Engineering – MBSE – is the formalized application of modelling to support the product development activities, from the beginning of the conceptual architecture phase over the development to the late phases of a systems lifecycle, concerning systems requirements, systems architecture, analysis, verification and validation [15, 16].

One of the challenges for present and future product development processes is to guarantee the reliability of increasingly complex systems. The ensuring of consistency in the product development, especially the traceability of requirements in strongly cross-linked systems with various players, is one of the key benefits of model based systems engineering. [17]

Systems Modeling Language (SysML) is a widely-used modeling language. With the help of system models based on this language product development information can be consistently managed. Furthermore, these models enable various views on the system at different levels of abstraction. Such approaches are required because an individual person cannot cope with the complexity of all its interdisciplinary dependencies. [16]

However, studies show a relatively great effort for development and usage of models. Thus, concepts are required which enable an efficient application of MBSE in product development. [18, 19]

2.3. MBSE in Modular Design

The approach of the product-generation-development can be applied to encounter the high expense using MBSE in product development. This concept implies that products are normally developed based on reference products (e. g. previous products or products from competitors) and innovative subsystems are added specifically [20].

This way, the development risk can be reduced and the development resources can be concentrated on the development of new subsystems. [21]

For the application of this approach, a special system modeling framework was developed. This framework enables a domain-independent classification of models in meta-models (such e. g. SysML), reference-models and product-models. In this way, over product generations unchanged elements can be efficiently managed in reference-models, so that these elements do not have to be modeled again [22].

A first study in the automotive sector has shown how the product development in modular design can be supported by this product-modeling-framework. The modelling framework especially for construction kit development and the results of the study are illustrated in figure 3 [23].

On the basis of a three year participatory observation, reference-product-models were identified and were chosen as foundation for modeling. Based on this, product-models and construction kit models are created. After that, new product generations can be modeled efficiently with the aid of a matrix-based product-representation, because existing subsystems can be integrated by adding relations between the system elements. A SysML-based product-modeling-concept enables the development of consistent models of construction kits and of their products themselves. These models can illustrate the system in different levels of abstraction using various views on the model [23].

3. Aim of research and research design

Previous studies [22, 23] have researched how the product modelling framework combined with the application of MBSE can support the development of products in modular design, by means of consistent modelling of modules and products. The aim of this paper is furthermore to introduce:

How the MBSE-based modelling of products and the corresponding construction kit can contribute to the identification of potential for product standardization?

For this purpose, a six month participatory observation study in cooperation with the thyssenkrupp Industrial Solutions AG was implemented. Thus it is possible to verify the transferability of the approach to another - previously not yet investigated - industrial sector - the machinery and plant engineering industry, using portal type scraper reclaimers as an example.

In the process chain between mining, processing and transshipping, bulk materials are often stored temporarily. These stockyards have a central function in the field of materials handling and serve as material buffers, reserve or blending storage and balance out fluctuations in the quantity and quality of raw material. Different stockyard systems such as stackers, stacker-reclaimers, bucket wheel reclaimers, drum reclaimers and bridge type or portal type scraper reclaimers are used for stacking and reclaiming of bulk materials (see figure 4). [24]

Figure 4: A typical bulk materials stockyard [25]

In the context of the initial situation analysis, existing portal type scraper reclaimers, designed and built by thyssenkrupp Industrial Solutions, should be modeled in SysML using the MBSE-based product modelling framework. The development and implementation of a construction kit model should gain long term potentials for the modularization in the development of new bulk materials handling machinery.

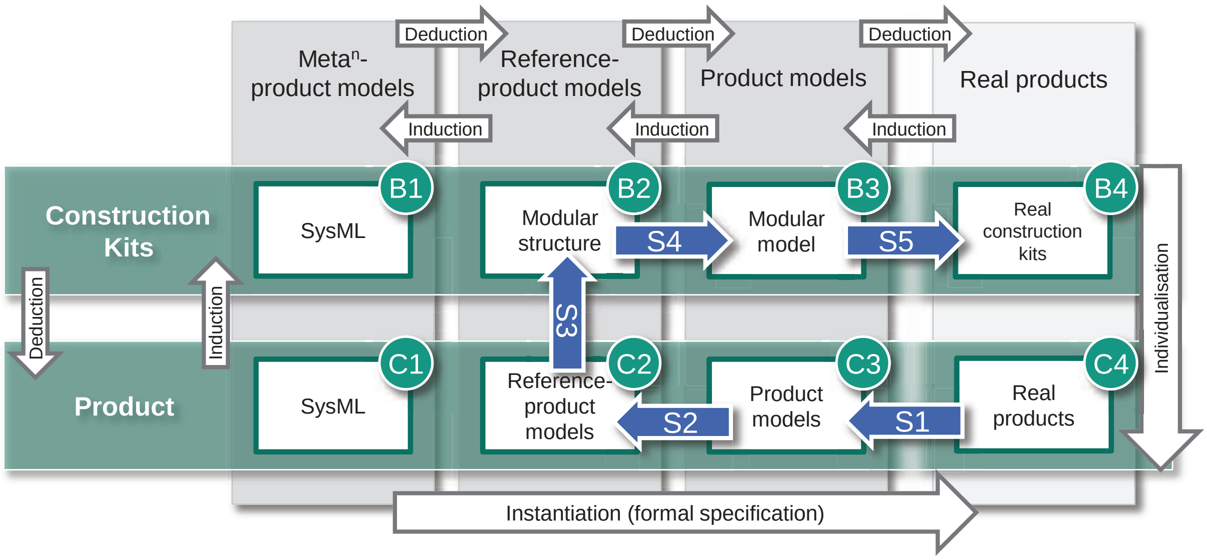

Figure 3: Model based construction kit development framework [23]

4. MBSE for a potential analysis using portal type scraper reclaimers as an example

Portal type scraper reclaimers are typical investment goods which are developed and built in very small quantities. The individuality of these products is common in this industry because stockyard machines are usually integrated into existing or new overall plants, such as for example coking plants, steelworks, cement plants, fertilizer plants or shipping terminals for bulk materials handling. At the beginning and during the product development process of new plant machinery, customers have the opportunity to specify their objectives, requirements, requests and marginal conditions. In spite of the individuality of these single machines, the development of portal type scraper reclaimers can also be described with the approach of product-generation-development because previous products as well as existing portal type scraper reclaimers are used as reference products for the development of a new product.

Regarding the modeling framework for construction kit development in figure 3, the development of a construction kit seems to be an obvious transition (induction) from a real product (C4) to a real construction kit (B4) respectively on model level from a product model (C3) to a construction kit model (B3). In the real practice, this way is not trivial, so that another concept with the consideration of various levels of modelling is regarded as an expedient path.

In the context of the case study the following framework based approached was chosen in four steps (S1-S5 in figure 3):

S1: In a first step, existing products (C4) and their documentation are analyzed and corresponding product models (C3) are created. These product models (C3) are representations of certain individual product variants.

S2: By an abstraction in a second step (S2) of the characteristics in the product models, these elements can be transferred into a common reference product model (C2). The reference product model (C2) includes an abstract description of the possible variants of a product.

S3: A following iterative adaption and enlargement of the reference product model (C2) with further product models (C3) and reference models (C2) of other products leads to a cross products reference model (B2).

S4: This way the sum of all product models (B3). The cross products reference model (B2) is a structural description of a construction kit for one or more products. The model of the sum of all product models (B3) describes a construction kit in its structural level as well as in all its possible characteristics.

S5: Thus, a real construction kit (B4) can be created by implementing such an overall construction kit model (B3) into reality. Finally, with the help of this real construction kit (B4) real products (C4) can be configured; respectively with the help of a construction kit model (B3) product models can easily be deduced.

The framework-based SysML-model, especially the overall model regarding the sum of all product models (B3), can also be used to represent the current situation of a product portfolio at the beginning of the development process. Thus, this framework-based modeling approach is a basis for a situation analysis with the aim to illustrate the existing variant diversity and to identify synergy potentials for a construction kit development.

SysML as actually common used meta-product-model in MBSE was also used in the case study as modeling language. In the context of the document analysis of the case example portal type scraper reclaimers, no reference-product-models (C2) could be found. So, these reference-product-models (C2) were developed on the basis of previously existing product generations. With the help of the reference-product-models (C2), it was possible to create construction kit models (B2 and B3) as well as to deduce product models (C3) efficiently. Thus, consistent models of the construction kit and of the included products themselves could be shown in a matrix-based illustration.

On the basis of an existing portal type scraper reclaimer (C4), a product model (C3) with various elements, such as for example the system environment, objectives, requirements and marginal conditions as well as functionalities and physical components, was created. The interactions of these elements can also be modeled regarding to [26]. An example is shown in figure 5.

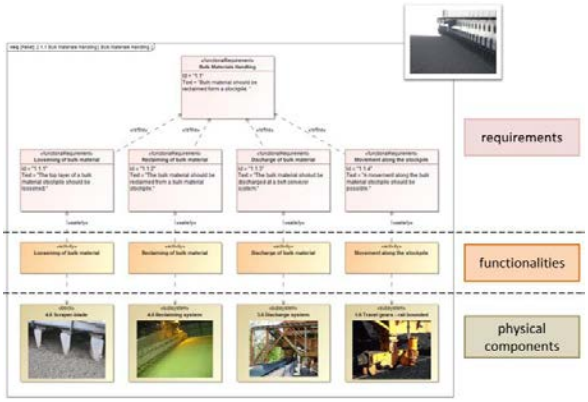

Figure 5: SysML modeling diagram

The information from numerous documents of product development (requirements lists, specifications, CAD-data …) are analyzed and transferred into a consistent and model based product model (C3). On this basis, a reference-product-model (C2) can be deduced. Using this procedure, the existing reference-product-model (C2) can be enlarged efficiently with additional portal type scraper reclaimers. In this step, the reference-product-model (C2) is iteratively adopted and transferred into a reference construction kit model (B2) and finally into an overall construction kit model (B3). In this way, the sum of all scraper blades can be visualized for instance (see figure 5). The structural elements (SysML-blocks) of a scraper blade assembly (blade, tear tooth and wear plate) as well as their dependencies have already been included in the reference construction kit model (B2). These structural elements contain the necessary properties of the physical components (e.g. the width and height of a scraper blade), but without any characteristics of the properties. These specific characteristics of the properties (e.g. width of a scraper blade: 2000mm) are completely contained in the overall construction kit model (B3). For this purpose, SysML offers the possibility to model instances of block-elements. With this tool, each occurring variant in the physical components structure as well as in the requirements structure can be modeled. Figure 6 shows the scraper blade example.

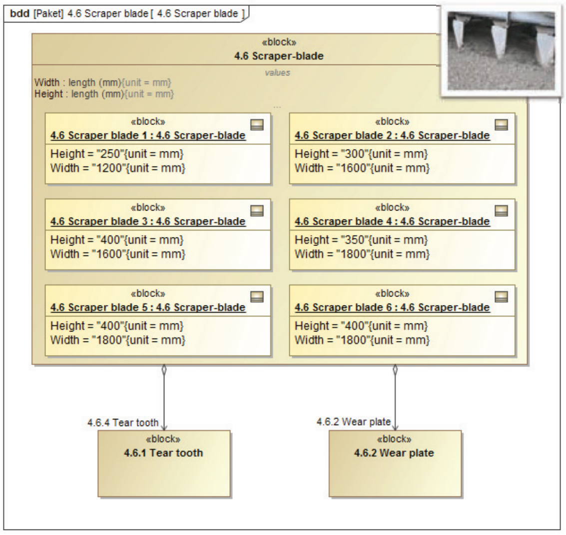

Figure 6: Scraper blades in construction kit model

Due to the large number of property characteristics and dependencies between the modeling elements, a matrix-based model representation is useful for reasons of clarity. The generated model of a current product portfolio situation can serve as a consistent database for various analyses. For instance, figure 7 shows an analysis regarding the frequency distribution of scraper blades. The existing variant diversity of the requirements structure (objectives, requirements and marginal conditions) is analogously modeled and can also be illustrated in a matrix-based representation. Hence, analyses related to the physical components structure are possible. For example, figure 8 shows a very inhomogeneous frequency distribution of the key requirement "bulk materials handling capacity".

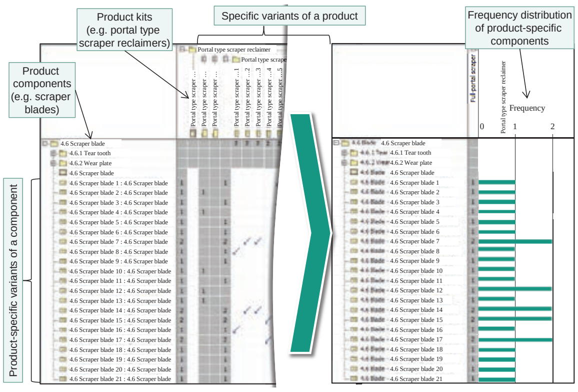

Figure 7: Frequency distribution of scraper blades

A comparison of the frequency distributions of the requirements structure elements and corresponding physical product structure components can detect indications regarding product standardization potentials. The concrete scraper blade example shows that the existing variant diversity of scraper blades (physical component) is significantly larger than the diversity of the requirement "bulk materials handling capacity". As a consequence, a potential for a limitation of the existing component diversity can be assumed.

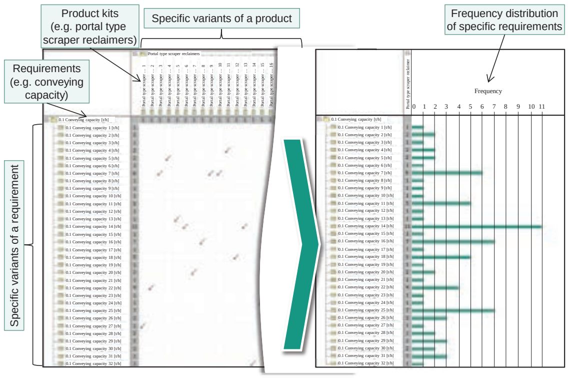

Figure 8: Frequency distribution of conveying capacity

Furthermore, it should be also considered that a physical product component often depends on a wide range of requirements. Hence, a lot of complex analyses are necessary to get a meaningful evaluation. Such potential analyses can support product developers and serve them as a basis in order to find indications with regard to the elements (assemblies and components) that have to be investigated.

An additional benefit of this model based construction kit development is the possibility to represent systems with fractal character. For instance, scraper blades (see figure 5) can be built according to the platform design type. In this case, the basic element of the scraper blade should be considered as platform and the hat section includes tear teeth and wear plates. Thus, different standardization methods can be used on several system levels. In systems with fractal character, this kind of modeling supports product developers to choose the right standardization approach for each system level.

In further steps, the results of product standardization can be integrated into the SysML-model to represent a consistent construction kit. Especially with strongly iterative product development processes, this approach offers a potential because the model is internally consistent and the evaluations can be deduced specifically.

In contrast, the document-centered modeling leads to the fact that any modification, addition or correction of information causes a revision of various documents. Particularly with regard to an iterative product development, at the beginning of such a development process it is unclear which aspects will be relevant. A consequent application of PGE - product generation engineering will be necessary to justify the additional expenses caused by SysML-modeling. Only the use of reference-product-models (C2) and the reuse of already modeled elements of previous product generations (B3) lead to a sufficient reduction in workload.

5. Conclusion and Outlook

In order to contribute to the product standardization, by using consistent SysML-models of products and corresponding construction kits the following findings could be made.

The MBSE models can be used as an information base for identifying potentials for standardization possibilities in a product portfolio. In the extremely iterative early stages of product development, new analyses can be efficiently realized, because the information is represented in an integrated and consistent system model rather than in isolated documents (such as e. g. requirements or design specifications). This way, some benefits concerning the application of the abstract modeling language SysML in practical development work can be contributed.

The necessary additional efforts can be justified, if a consistent product model is created and refined over several product generations. Thus, the reference-product-models and some components can be reused in future product generations.

If the construction kit development is considered as a continuous activity which proceeds in parallel to the development of the individual products, there will be further need for research. New methods and processes which encounter the iterative character of a product and construction kit development will be required. For this purpose, a three- year accompanying study is carried out in cooperation with a machine tool manufacturer to support the product developers concerning the implementation of real construction kits.

The approach of the present paper was analyzed in the context of the following construction kit characteristics: manufacturer construction kit, closed construction kit, structure-bound construction kit and mixed system. Furthermore, the transferability of the presented MBSE-approach to other construction kit characteristics shall be researched in future projects to get an integrated and helpful support concept for product developers.

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